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# **DYNAMIC STABILITY RESULTS FOR SHARP AND BLUNTED 10-DEG CONES AT HYPERSONIC SPEEDS**

**L. K. Ward, Jr. and B. L. Uselton**

**ARO, Inc.**

**December 1968**

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*Roy R. Croy, Jr.*

**ROY R. CROY, JR., Colonel, USAF  
Director of Test**

DYNAMIC STABILITY RESULTS FOR SHARP  
AND BLUNTED 10-DEG CONES AT HYPERSONIC SPEEDS

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## FOREWORD

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Eugene C. Fletcher  
Lt Colonel, USAF  
AF Representative, VKF  
Directorate of Test

Roy R. Croy, Jr.  
Colonel, USAF  
Director of Test

## ABSTRACT

Tests were conducted in Tunnel C of the von Kármán Gas Dynamics Facility to obtain dynamic stability data for sharp and blunted 10-deg half-angle cones. With both a free-oscillation gas bearing pivot balance system and a forced-oscillation cross-flexure pivot balance system, data were obtained at a nominal Mach number of 10 at free-stream Reynolds numbers, based on model length, ranging from  $1.80 \times 10^6$  to  $3.19 \times 10^6$ . The effects of boundary-layer transition, amplitude of oscillation, nose bluntness, and model center-of-gravity location on the dynamic and static stability derivatives are presented. Comparison of data from the free- and forced-oscillation test techniques and the effect of frequency of oscillation on the damping-in-pitch derivatives are also presented. The derivatives are compared with steady and unsteady flow field theories.

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## NOMENCLATURE

$A$	Reference area (model base area), $\text{ft}^2$
$C_N$	Normal-force coefficient, normal force/ $q_\infty A$
$C_{N\alpha}$	$\partial C_N / \partial \alpha$ , 1/rad
$C_m$	Pitching-moment coefficient, pitching moment/ $q_\infty A d$
$C_{mq}$	$\partial C_m / \partial (qd/2V_\infty)$ , 1/rad
$C_{m\alpha}$	$\partial C_m / \partial \alpha$ , 1/rad
$C_{m\dot{\alpha}}$	$\partial C_m / \partial (\dot{\alpha}d/2V_\infty)$ , 1/rad
	} Effective values
$d$	Reference length (model base diameter), ft
$L$	Virtual model length (see Fig. 5), ft
$\ell$	Actual model length (see Fig. 5), ft
$M_\infty$	Free-stream Mach number
$q$	Pitching velocity, rad/sec
$q_\infty$	Free-stream dynamic pressure, $\text{lb/ft}^2$
$Re_L$	Free-stream Reynolds number based on virtual model length
$Re_\ell$	Free-stream Reynolds number based on model length
$Re/\ell$	Free-stream unit Reynolds number, 1/ft
$r_b$	Model base radius, in.
$r_n$	Model nose radius, in.
$V_\infty$	Free-stream velocity, ft/sec
$X_{cg}$	Distance from virtual model nose to pivot axis (see Fig. 5), ft
$x_{cg}$	Distance from model nose to pivot axis (see Fig. 5), ft
$\alpha$	Angle of attack, rad
$\dot{\alpha}$	Time rate of change of angle of attack, rad/sec
$\theta$	Oscillation amplitude, deg

$\theta_c$  Cone half-angle, deg

$\omega$  Angular frequency, rad/sec

$\omega d/2V_\infty$  Reduced frequency parameter, rad

**SUBSCRIPT**

o Moment reference at the nose

## SECTION I INTRODUCTION

The purpose of this report is to present recent dynamic stability data that were obtained on sharp and blunted 10-deg half-angle cones in the 50-in. VKF tunnel (Gas Dynamic Wind Tunnel, Hypersonic (C)) at a nominal Mach number of 10.

The measurements were made at a free-stream Reynolds number that was sufficiently low to provide a laminar boundary layer on the model surface when the model was oscillating  $\pm 2$  deg. For completeness of the report, the effects of Reynolds number, or rather the effects of boundary-layer transition, on the static and dynamic derivatives will be reviewed. In addition, the effects of oscillation amplitude and center-of-gravity location on the static and dynamic stability derivatives will be shown along with the effects of frequency of oscillation on the pitch derivatives at Mach 10. The data will be compared with predictions of steady (static stability only) and unsteady flow field theories.

## SECTION II APPARATUS

### 2.1 WIND TUNNEL

Tunnel C is a continuous, closed-circuit, variable density wind tunnel with an axisymmetric contoured nozzle and a 50-in.-diam test section. The tunnel can be operated at a nominal Mach number of 10 or 12 at stagnation conditions from 200 to 1850 psia at 1900°R and from 600 to 2000 psia at 2350°R, respectively. The model may be injected into the tunnel for a test run and then retracted for model cooling or model changes without interrupting the tunnel flow. A description of the tunnel may be found in Ref. 1. A summary of the test conditions is given in Table I (Appendix II).

### 2.2 BALANCES

#### 2.2.1 Free-Oscillation Balance

The one-degree-of-freedom dynamic balance used in the present tests is a large amplitude ( $\pm 15$ -deg) system incorporating a cylindrical gas bearing as the pivot. The balance has an angular transducer which provides an analog signal proportional to model amplitude, yet requires no physical contact between the moving and stationary parts of the bearing. A more complete description of the system may be found in Ref. 2.

### 2.2.2 Forced-Oscillation Balance

The small amplitude ( $\pm 3$ -deg) forced-oscillation balance system used in the present tests is a one-degree-of-freedom oscillatory system incorporating a cross-flexure pivot and is forced to oscillate by an electromagnetic shaker motor. Additional information concerning the balance may be found in Ref. 2.

### 2.3 MODEL

The model used in the present tests was a 10-deg half-angle cone ( $d \approx 10$  in.) and had a series of removable noses to provide nominal bluntness ratios ( $r_n/r_b$ ) of 0, 0.15, and 0.3. The model was balanced so that the model balance center of gravity was located at the balance pivot axis.

## SECTION III DATA REDUCTION

### 3.1 FREE-OSCILLATION TESTS

Neither the static nor the dynamic derivatives for the blunted cones were constant with oscillation amplitude. The differential equation describing the motion is, therefore, nonlinear. The log decrement technique (linear theory) may still be used in cases when the aerodynamic stiffness ( $C_{m\alpha}$ ) is linear by applying the linear theory over small time increments where the motion is nearly exponentially damped. When the aerodynamic stiffness varies with oscillation amplitude, errors in the damping factor are introduced by using the linear theory as shown by Nicolaides in Ref. 3. The complete nonlinear data reduction techniques used in these tests are presented in detail in Ref. 4.

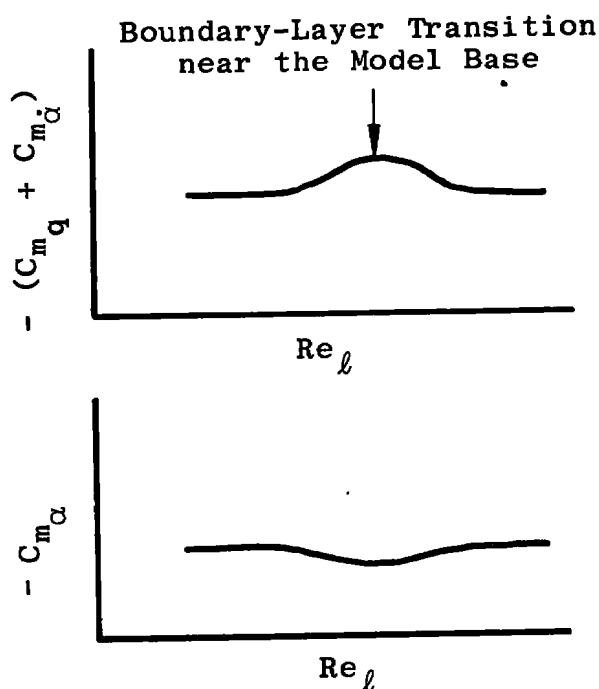
### 3.2 FORCED-OSCILLATION TESTS

The forced-oscillation data were obtained at the natural undamped frequency of the model-balance system. The models were oscillated in a vacuum chamber at pressures ranging from 0.5 psia to atmospheric pressure in order to determine the damping resulting from ambient pressure. The complete data reduction procedures may be found in Ref. 4.

## SECTION IV RESULTS AND DISCUSSION

### 4.1 EFFECTS OF BOUNDARY-LAYER TRANSITION

During the course of an experimental study to determine the effects of support interference on the dynamic stability of a sharp 10-deg cone at supersonic speeds, Uselton (Ref. 5) found that there existed a consistent rise in the damping derivatives ( $C_{m\dot{q}} + C_{m\dot{\alpha}}$ ) and fall in the static derivative ( $C_{m\alpha}$ ) as shown in the sketch below. The maximum and minimum values of  $C_{m\dot{q}} + C_{m\dot{\alpha}}$  and  $C_{m\alpha}$ , respectively, were found to occur when boundary-layer transition, (the beginning of fully developed turbulent flow) as detected by schlieren photographs and base pressure measurements, was near the model base. Reynolds number had no effect on the static or dynamic derivatives if the model boundary layer remained laminar or near fully turbulent throughout the model oscillation amplitude range. These same trends were observed by Ward at hypersonic speeds as reported in Ref. 6. Typical data from the above sources are shown in Fig. 1 (Appendix I).



Jaffee and Prislin conducted wind tunnel tests at the Jet Propulsion Laboratory (JPL) using the wind tunnel free-flight technique in order to investigate the effect of boundary-layer transition on the dynamic stability of sharp, 10-deg half-angle cones (Ref. 7). A conclusion reached during the course of that work was that the nature of the boundary layer and the position of transition did not affect the dynamic stability of 10-deg half-angle cones. Later work, however, at JPL by Prislin (Ref. 8) using 10-deg half-angle cones led him to conclude that Reynolds number had a significant influence on the dynamic stability of sharp cones.

In the earlier JPL work mentioned above (Ref. 7), a series of boundary-layer trips was used to promote transition and to provide

several "effective" Reynolds numbers for one free-stream tunnel condition. Studies were made only at zero angle of attack when the trip sizes were selected, and estimates were made where transition would be moved for the maximum trip diameter used. It is well documented (for example, see Refs. 6, 9, and 10) that as a cone is yawed, transition will move forward on the leeward side and slightly rearward on the windward side. McCauley et al. (Ref. 10) have shown, however, that when trips are used the reverse may be true. This is readily apparent when one considers the physical situation at the trip location on a yawed cone. The boundary layer on the windward side has thinned making the trip more effective, whereas the boundary layer on the leeward side has become thicker making the trip less effective. It is certainly probable that boundary-layer trips could subdue or even reverse the established trends noted in the sketch and explained by Ericsson in Ref. 11 as being caused by viscous time-lag effects.

Now that the effects of boundary-layer transition on the static and dynamic stability of cones have been established, it should become clear that one should not consider this a Reynolds number effect when attempting to compare data from one tunnel to another. Rather, the data should be compared on the basis of the transition Reynolds numbers for each wind tunnel. Pate and Schueler provide in Ref. 12 conclusive proof that transition Reynolds number is a function of tunnel size. It should also be apparent that when wind tunnel data are compared with theory, one should compare data obtained either before or after the rise in the dynamic stability as depicted in the sketch.

#### 4.2 EFFECTS OF NOSE BLUNTNESS

Typical dynamic and static stability data obtained on a 10-deg half-angle cone during the present tests at  $M_\infty \approx 10$  with bluntness ratios ( $r_n/r_b$ ) of 0.001, 0.151, and 0.300 are shown in Fig. 2 as a function of oscillation amplitude. These data are from models tested with the center of gravity at a point 60 percent aft of the virtual length of the cone ( $X_{cg}/L = 0.60$ ). The damping derivatives ( $C_{m_q} + C_{m_{\dot{\alpha}}}$ ) and static stability derivatives ( $C_{m_\alpha}$ ) for the sharp cone were constant over the amplitude range tested. For the blunted cones, the static stability derivative was not constant with oscillation amplitude ( $\theta$ ) but decreased with amplitude for  $r_n/r_b = 0.151$  and increased with amplitude for  $r_n/r_b = 0.300$ . The damping for both blunted cones increased with amplitude. The unsteady flow field theory (Refs. 13 and 14) agrees well with all derivatives as  $\theta$  approaches zero, although the theory predicts somewhat lower values of damping ( $C_{m_q} + C_{m_{\dot{\alpha}}}$ ) and somewhat higher values of  $C_{m_\alpha}$  for the blunted cones.

Although not shown, similar trends with amplitude were found for the static and dynamic derivatives ( $C_{m_\alpha}$  and  $C_{m_q} + C_{m_{\dot{\alpha}}}$ ) at  $M_\infty = 10$

with the pivot axis at 65 percent of the cone virtual length ( $X_{cg}/L = 0.65$ ). The levels of the derivatives obtained at  $\theta = \pm 2$  deg are shown in Fig. 3 as a function of nose bluntness ratio ( $r_n/r_b$ ) and are compared with the unsteady flow field theory (Ref. 14). Again, the agreement with theory is best for the sharp cone data. It is interesting to note the variation with nose bluntness that the theory predicts for both  $C_{m_q} + C_{m_{\dot{\alpha}}}$  and  $C_{m_{\alpha}}$ . Additional experimental data are needed at bluntness ratios between  $r_n/r_b = 0$  and 0.15 to confirm the trends predicted by the theory.

Clay conducted experiments at  $M_\infty = 14.2$  at the Aerospace Research Laboratory (Ref. 15) to determine the effects of nose bluntness on  $C_{m_q} + C_{m_{\dot{\alpha}}}$  and  $C_{m_{\alpha}}$  of a 10-deg half-angle cone. These data are compared in Fig. 4 with flow field theory (Ref. 14). The model moment reference point (model pivot axis) was held constant with respect to the cone virtual length at  $X_{cg}/L = 0.608$ . The measured damping derivatives ( $C_{m_q} + C_{m_{\dot{\alpha}}}$ ) agree with the theory at  $r_n/r_b = 0$  and 0.15 and are higher than the theory at  $r_n/r_b = 0.30$ , as was the case with the present  $M_\infty = 10$  data in Fig. 3. At  $r_n/r_b < 0.15$ , the trend predicted by the theory was not confirmed by these data. The  $C_{m_{\alpha}}$  data were in better agreement with the trend predicted by the theory.

It is interesting to observe that the original work done by Brong (Ref. 13) on the unsteady flow field solutions for a sharp cone yielded  $C_{N_{\alpha}}$  values which agreed precisely with the Stone-Kopal results (referred to herein as Conical Flow Theory) for the steady-state solution. The extension of Brong's work to include blunted cones as reported by Rie et al. in Ref. 14 provides a  $C_{N_{\alpha}}$  value that does not approach the Conical Flow Theory as  $r_n/r_b$  approaches zero. The theoretical values,  $C_{N_{\alpha}}$  and  $C_{m_{\alpha}}$ , from Ref. 14 are shown in Fig. 5 as a function of  $r_n/r_b$  for a 10-deg cone at  $M_\infty = 10$ . One may see that  $C_{N_{\alpha}}$  does not approach the level provided by Conical Flow Theory. Note the Conical Flow Theory for  $C_{m_{\alpha}}$  (Fig. 5). This curve was obtained by ignoring the physical nose bluntness of the cone and determining the distance to the center of gravity from the virtual nose of the cone ( $X_{cg}$ ) and using the virtual length of the cone ( $L$ ) to obtain  $X_{cg}/L$ . Values of  $C_{m_{\alpha}}$  may then be obtained by using the following well-known equations for sharp cones:

$$C_{m_{\alpha}} = C_{m_{\alpha 0}} + \left( \frac{X_{cg}}{L} C_{N_{\alpha}} \right) \frac{L}{d}$$

where

$$C_{m_{\alpha 0}} = - \frac{2}{3} \sec^2 \theta_c C_{N_{\alpha}} \frac{L}{d}$$

and

$$C_{m_{\alpha}} = \left( \frac{X_{cg}}{L} - \frac{2}{3} \sec^2 \theta_c \right) C_{N_{\alpha}} \frac{L}{d}$$



It would seem that this approximation for  $C_{m\dot{\alpha}}$  may be a more valid estimate than the unsteady flow field theory of Ref. 14 if one limits its use to very small values of  $r_n/r_b$ . The limit for this case ( $\theta_c = 10$  deg,  $M_\infty = 10$ ) would appear from Fig. 5 to be  $r_n/r_b \approx 0.07$ . In addition, one must use caution when comparing experimental results of near sharp cones with the theory for sharp cones and should ensure that the proper reference lengths are used.

The unsteady flow field theory of Ref. 14 has been plotted in Fig. 6 to show the effects of nose bluntness on  $C_{m\dot{q}} + C_{m\dot{\alpha}}$  and  $C_{m\alpha}$  for a 10-deg half-angle cone at  $M_\infty = 10$  for  $x_{cg}/l$  values ranging from 0.52 to 0.68.

#### 4.3 EFFECTS OF CENTER-OF-GRAVITY LOCATION

The variations of the damping derivatives ( $C_{m\dot{q}} + C_{m\dot{\alpha}}$ ) with center-of-gravity location ( $x_{cg}/l$ ) for sharp and blunted 10-deg half-angle cones at  $M_\infty = 10$  are shown in Fig. 7. The data were obtained at oscillation amplitudes ( $\theta$ ) of about  $\pm 2$  deg using the forced- and the free-oscillation techniques. The experimental data for  $r_n/r_b = 0.001$  appear to be scattered about the level of the unsteady flow field theory (Ref. 13). The data for  $r_n/r_b = 0.151$  are slightly above the theory (Ref. 14), whereas the level of the  $r_n/r_b = 0.300$  data is twice the level predicted by the theory.

The effect of center-of-gravity location ( $x_{cg}/l$ ) on cone static stability derivatives is shown in Fig. 8 as obtained by using both the free- and forced-oscillation techniques. The sharp cone data agree almost precisely with the unsteady flow field theory (Ref. 13). The  $r_n/r_b = 0.300$  data agree well with the theory (Ref. 14), but the same theory overpredicts the level of  $C_{m\alpha}$  measured for  $r_n/r_b = 0.151$ .

#### 4.4 EFFECTS OF REDUCED FREQUENCY

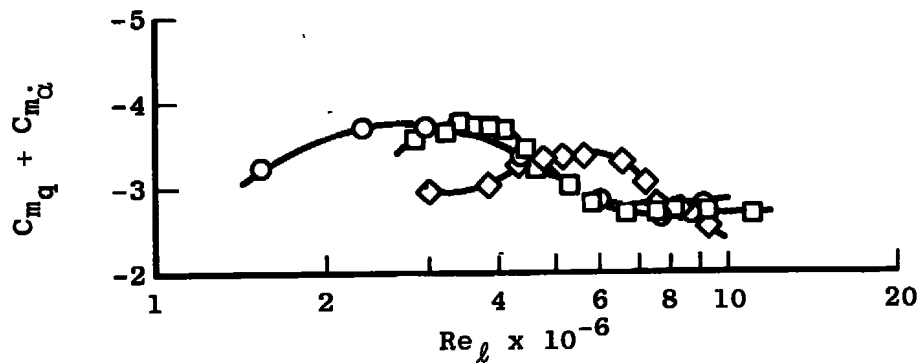
Figure 9 shows the effects of reduced frequency ( $\omega d/2V_\infty$ ) on the damping derivatives ( $C_{m\dot{q}} + C_{m\dot{\alpha}}$ ) for 10-deg cones with bluntness ratios ( $r_n/r_b$ ) of 0.001, 0.151, and 0.300. The data were obtained at  $M_\infty = 10$  and at free-stream Reynolds numbers ( $Re_\ell$ ) ranging from  $1.80 \times 10^6$  to  $3.19 \times 10^6$  using the free- and forced-oscillation techniques. The data show that the damping derivatives increased with  $\omega d/2V_\infty$  at some exponential rate. No conclusion on the effects of  $\omega d/2V_\infty$  on the damping derivatives will be drawn at this time. It does appear that additional experiments are needed to confirm these trends and to extend the range of  $\omega d/2V_\infty$ .

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**APPENDIXES**  
**I. ILLUSTRATIONS**  
**II. TABLE**



Sym	$M_\infty$	Source	Tunnel	$(\omega d/2V_\infty)$ , rad
○	3	Ref. 5	VKF-D	$\approx 0.012$
□	5	Ref. 6	VKF-E	$\approx 0.008$
◇	7	Ref. 6	VKF-E	$\approx 0.005$

$$r_n/r_b = 0.0167$$

$$x_{cg}/\ell = 0.550$$

$$X_{cg}/L = 0.556$$

$$\theta = \pm 2 \text{ deg}$$

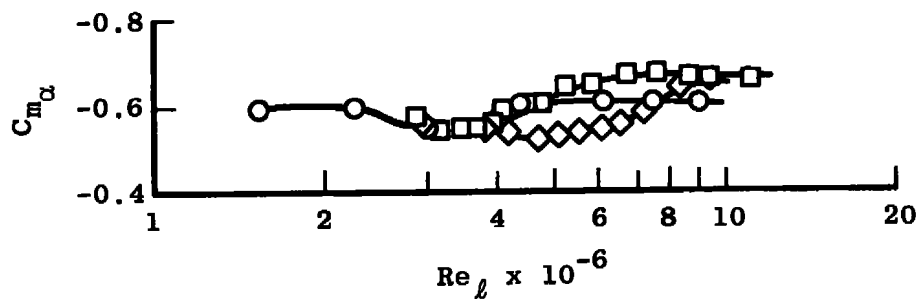
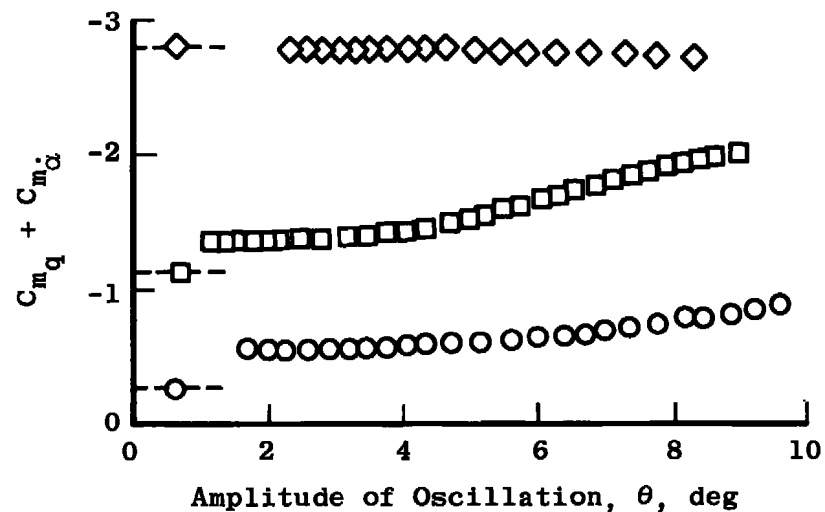
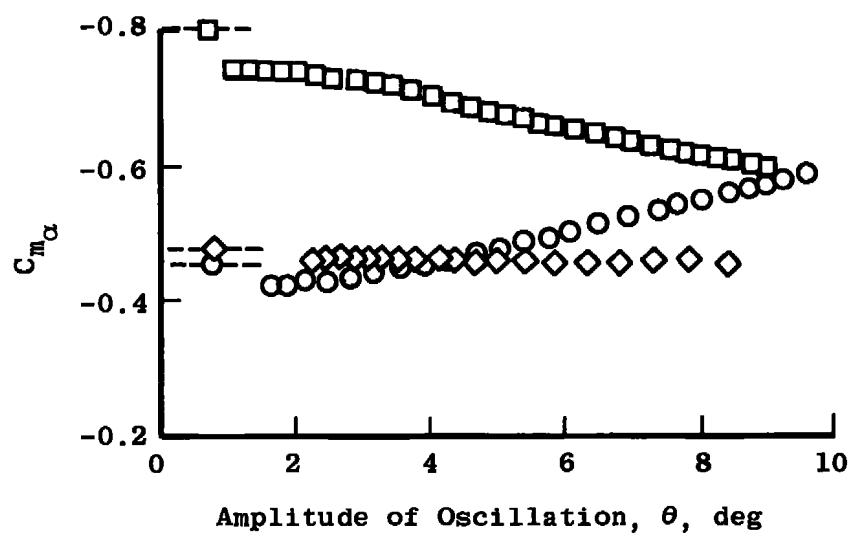


Fig. 1 Variation of Dynamic and Static Stability Derivatives with Reynolds Number ( $Re_\ell$ ),  $\theta_c = 10 \text{ deg}$


 $M_\infty \approx 10$ 

--- Unsteady Flow Field  
Theory (Refs. 13 and 14)



Sym	$r_n/r_b$	$x_{cg}/l$	$X_{cg}/L$	$\omega d/2V_\infty$	$Re_\ell \times 10^{-6}$
◇	0.001	0.600	0.600	0.0009	2.42
□	0.151	0.542	0.600	0.0015	3.19
○	0.300	0.465	0.600	0.0012	2.72

Fig. 2 Variation of Dynamic and Static Stability Derivatives with Amplitude of Oscillation

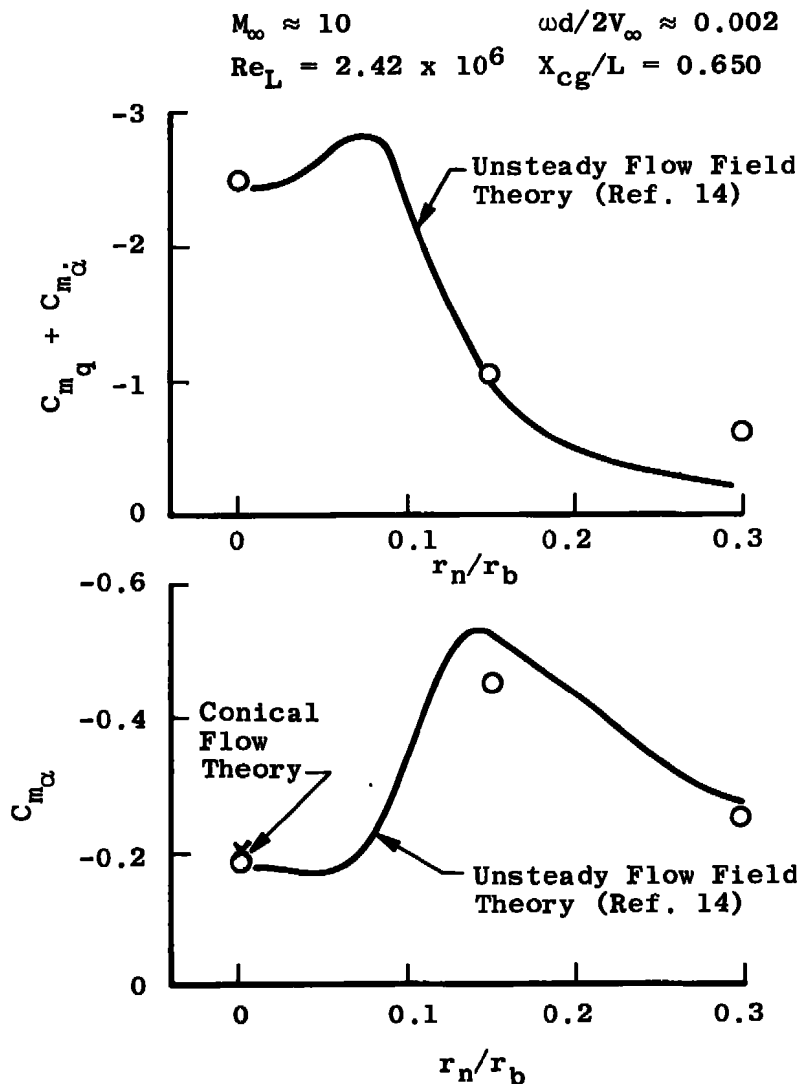


Fig. 3 Variation of  $C_{m_q} + C_{m_{\dot{\alpha}}}$  and  $C_{m_\alpha}$  with Nose Bluntness,  $\theta_c = 10$  deg,  $M_\infty \approx 10$

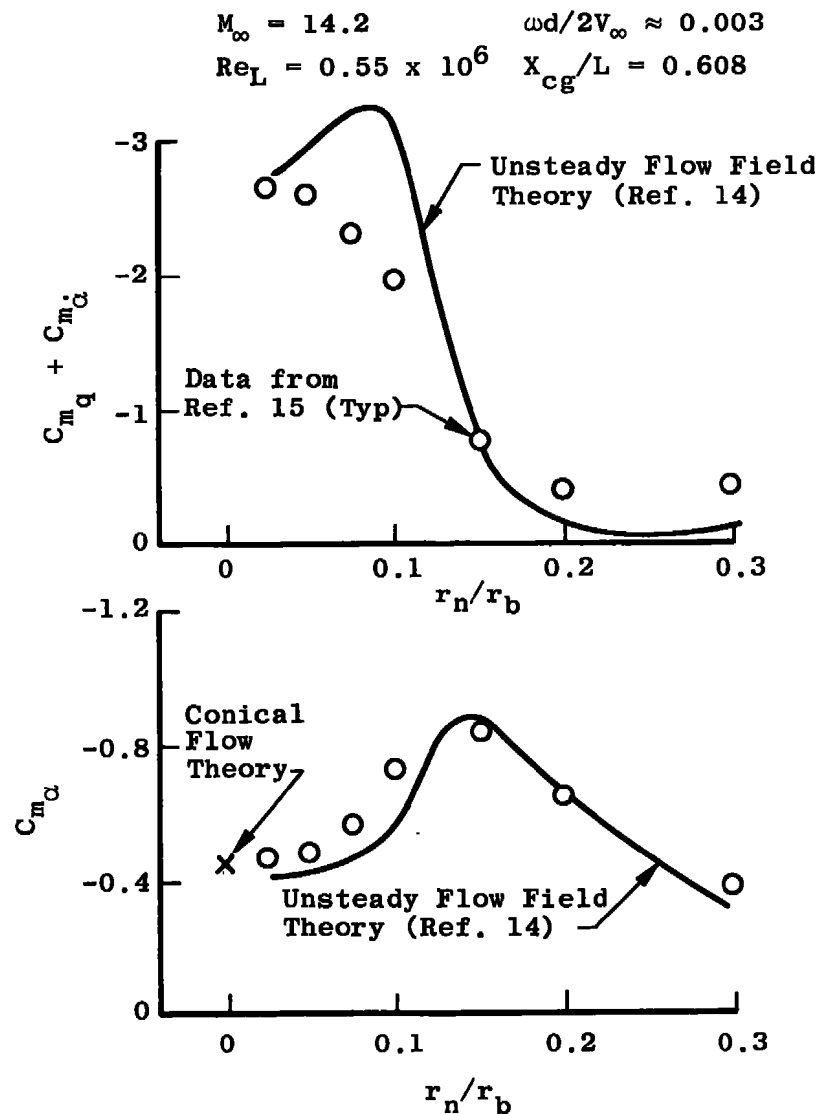


Fig. 4 Variation of  $C_{m_q} + C_{m_{\dot{\alpha}}}$  and  $C_{m_\alpha}$  with Nose Bluntness,  $\theta_c = 10$  deg,  $M_\infty = 14.2$

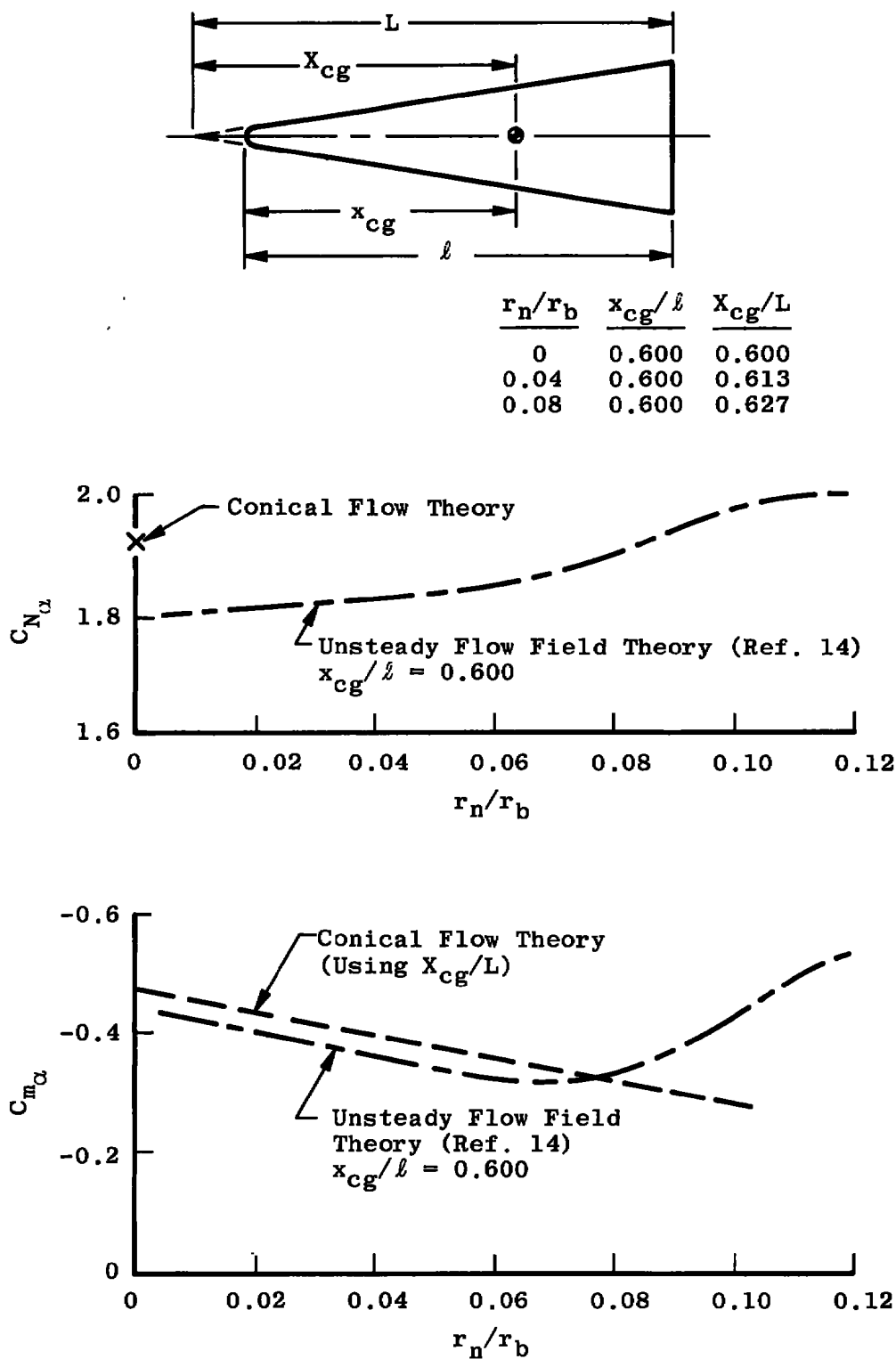


Fig. 5 Theoretical Predictions of  $C_{N\alpha}$  and  $C_{m\alpha}$  as a Function of Nose Bluntness Ratio ( $r_n/r_b$ ),  $\theta_c = 10$  deg,  $M_\infty = 10$



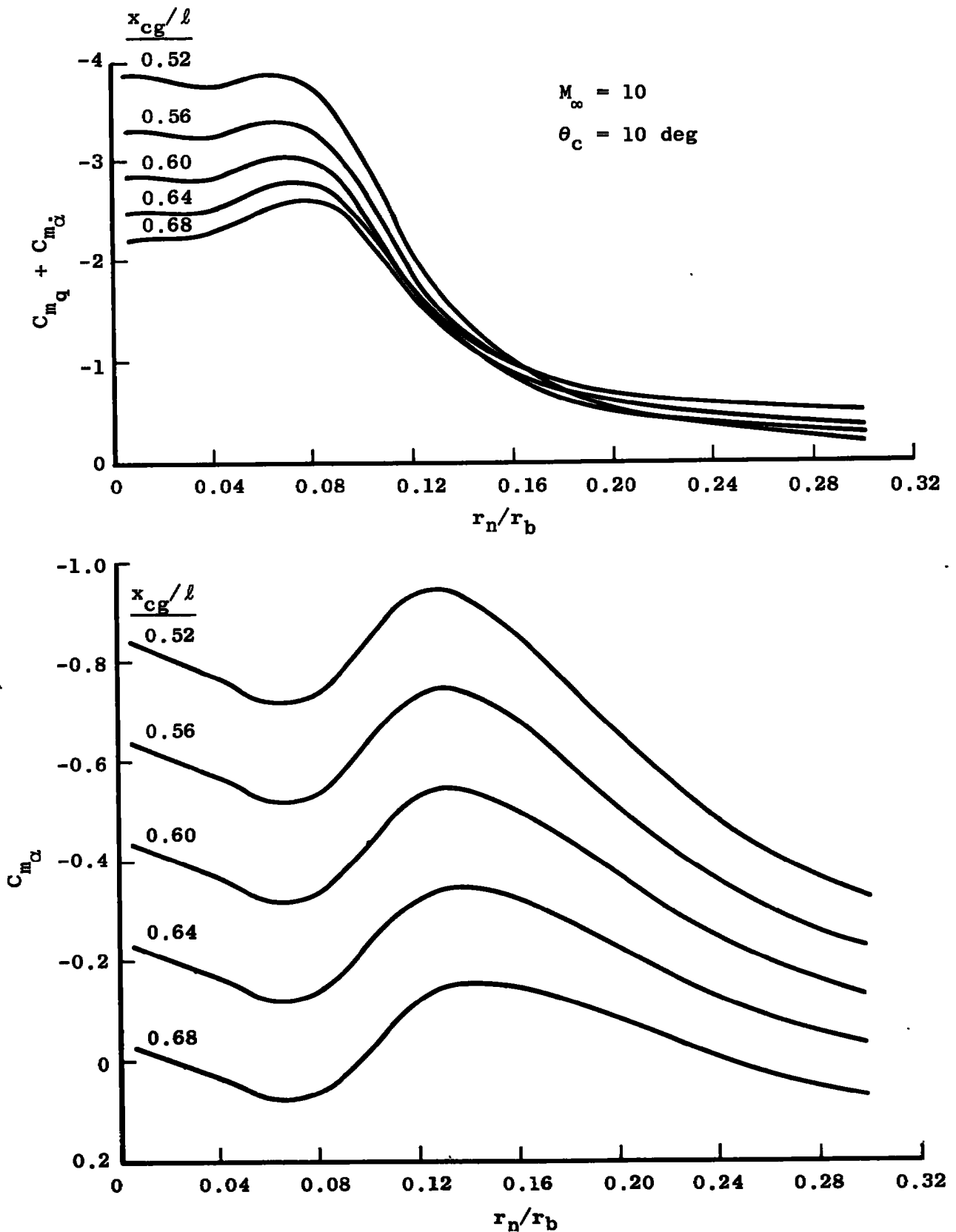
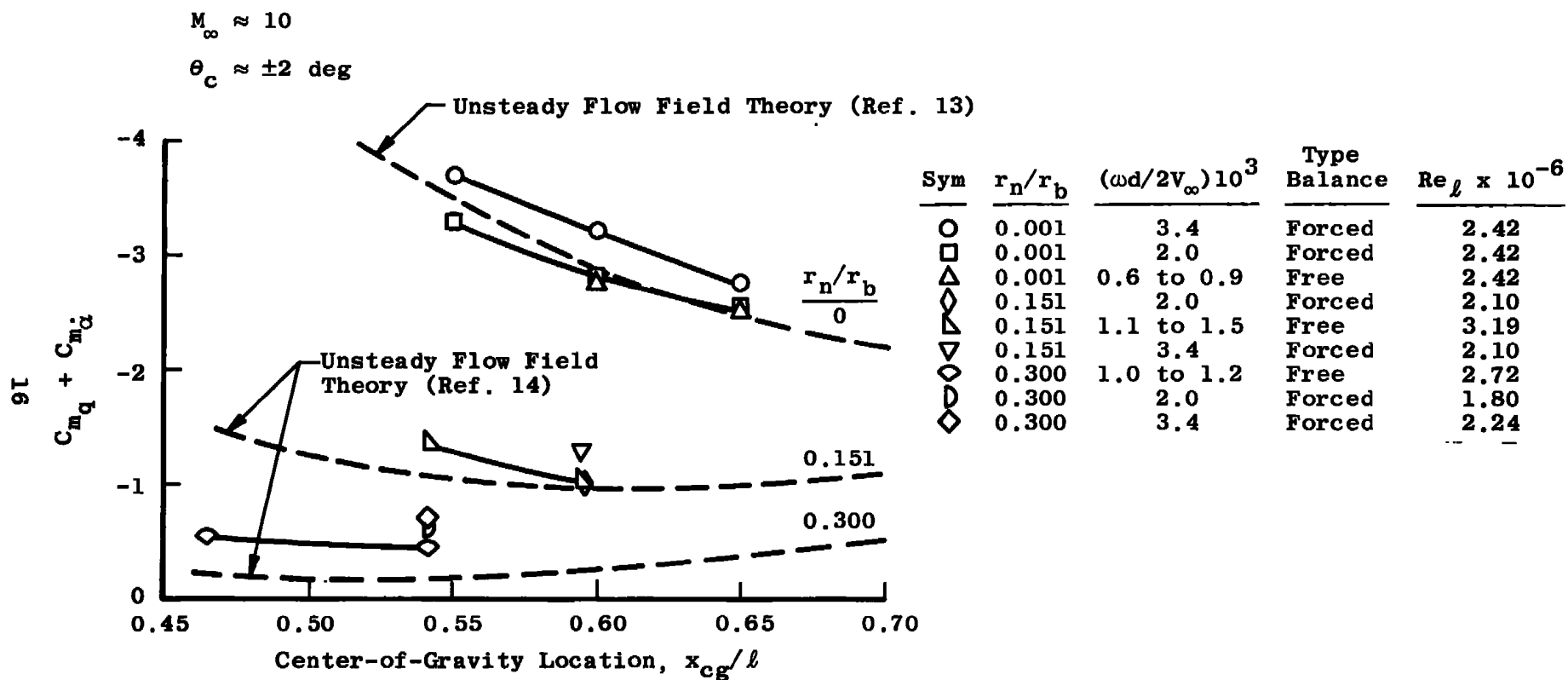


Fig. 6 Unsteady Flow Field Predictions of  $C_{m_q} + C_{m_{\dot{\alpha}}}$  and  $C_{m_\alpha}$  as a Function of  $r_n/r_b$  (from Ref. 14)

Fig. 7 Variation of  $C_{m_q} + C_{m_{\dot{\alpha}}}$  with Center-of-Gravity Location

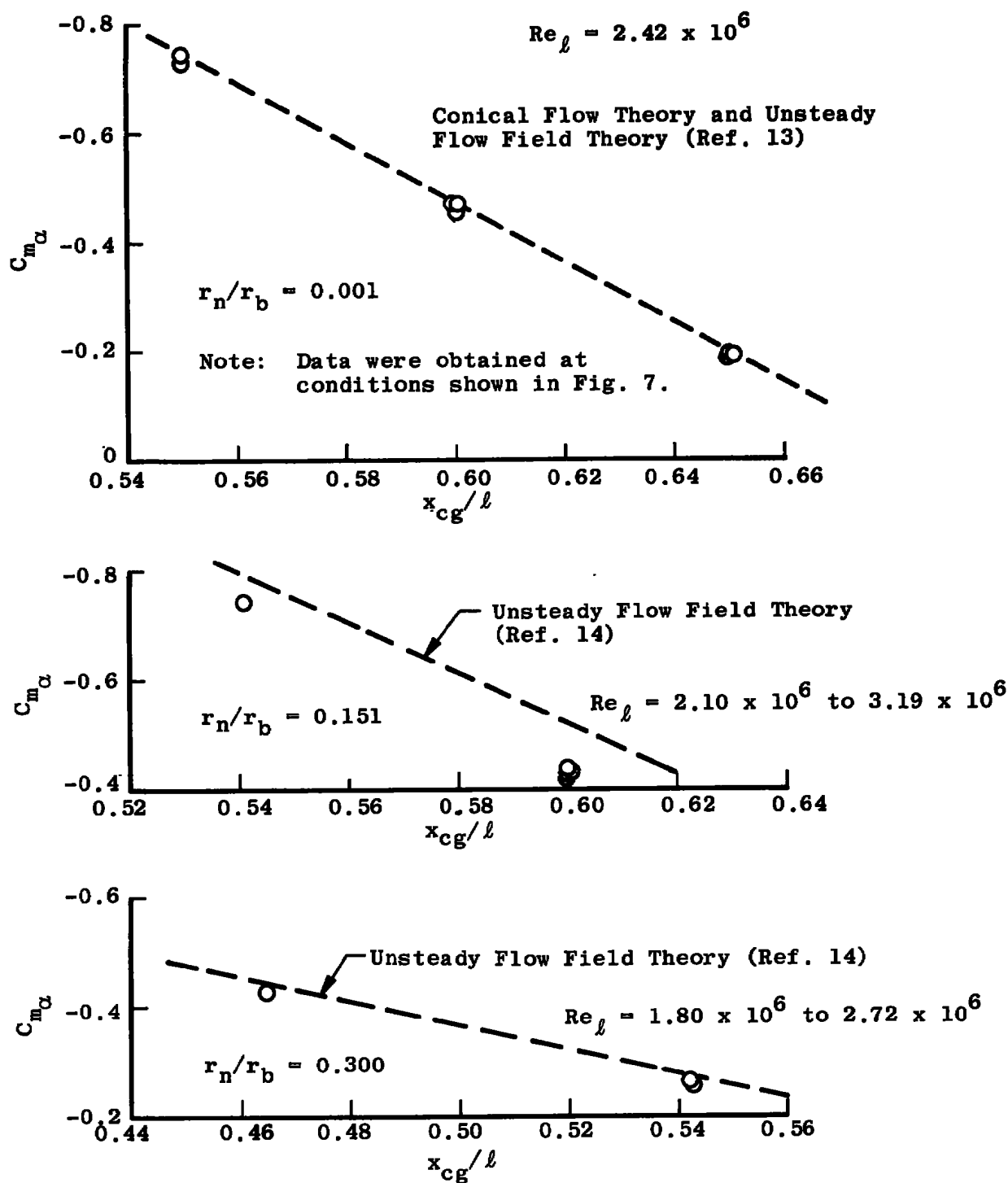


Fig. 8 Variation of  $C_{m\alpha}$  with Center-of-Gravity Location,  $\theta_c = 10$  deg,  
 $M_\infty \approx 10$ ,  $\theta = \pm 2$  deg

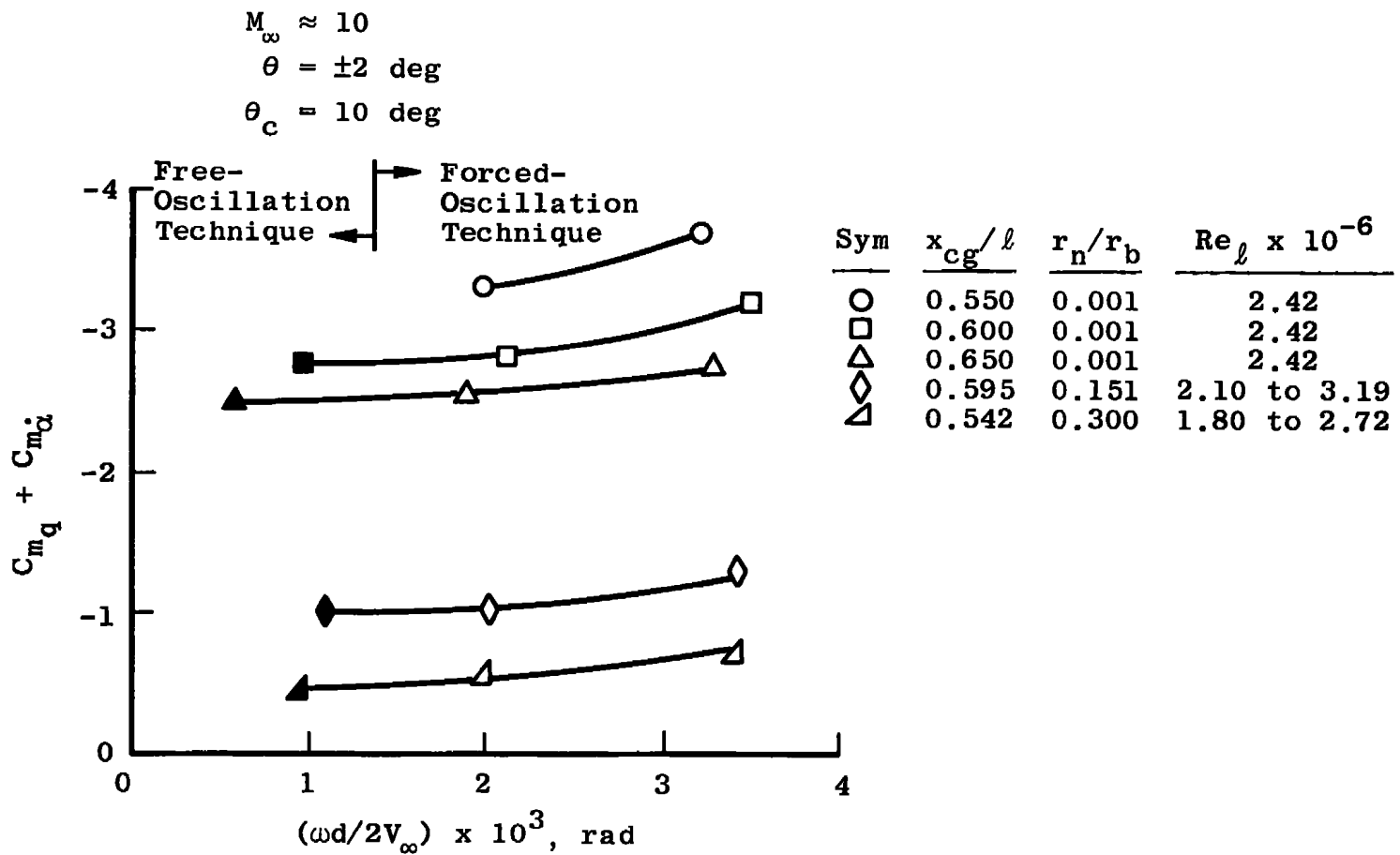


Fig. 9 Variation of  $C_{m_q} + C_{m_\alpha}$  as a Function of  $\omega d / 2V_\infty$

TABLE I  
SUMMARY OF TEST CONDITIONS

Model Conditions

Technique	$r_n/r_b$	$x_{cg}/l$	$X_{cg}/L$	$\approx (Re/l) \times 10^{-6}$	$\approx \omega d/2V_\infty \times 10^3$
Forced Oscillation ↓	0.001	0.550, 0.600, 0.650	0.550, 0.600, 0.650	1.02	2.0, 3.4
	0.151	0.595	0.650	1.02	2.0, 3.4
	0.300	0.542	0.650	1.02, 1.27	2.0, 3.4
Free Oscillation ↓	0.001	0.600, 0.650	0.600, 0.650	1.02	0.6 → 0.9
	0.151	0.542	0.600	1.54	1.5
	0.151	0.595	0.650	1.54	1.1
	0.300	0.465	0.600	1.54	1.2
	0.300	0.542	0.650	1.54	1.0

Tunnel Conditions

$(Re/l) \times 10^{-6}$	$M_\infty$	$q_\infty$ , psfa	$V_\infty$ , ft/sec
1.02	10.12	172	4690
1.27	10.14	215	↓
1.54	10.16	260	

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13. ABSTRACT  Tests were conducted in Tunnel C of the von Kármán Gas Dynamics Facility to obtain dynamic stability data for sharp and blunted 10-deg half-angle cones. With both a free-oscillation gas bearing pivot balance system and a forced-oscillation cross-flexure pivot balance system, data were obtained at a nominal Mach number of 10 at free-stream Reynolds numbers, based on model length, ranging from $1.80 \times 10^6$ to $3.19 \times 10^6$ . The effects of boundary-layer transition, amplitude of oscillation, nose bluntness, and model center-of-gravity location on the dynamic and static stability derivatives are presented. Comparison of data from the free- and forced-oscillation test techniques and the effect of frequency of oscillation on the damping-in-pitch derivatives are also presented. The derivatives are compared with steady and unsteady flow field theories.  This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of Arnold Engineering Development Center (AETS), Air Force Systems Command, Arnold Air Force Station, Tennessee 37389.			

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